Identification of Regional Soil Quality Factors and Indicators: II. Northern Mississippi Loess Hills and Palouse Prairie

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ABSTRACT

Diversity of soil series present in a region may hinder identification of soil quality factors and indicators at a regional scale. Our objectives were (i) to identify soil quality factors for a diverse population of soils at the regional scale, (ii) to determine which factors vary significantly with land use, (iii) to select indicators from these factors that can be used with the National Resource Inventory (NRI) for monitoring soil quality, and (iv) to compare these results to a similar study involving only a single soil series. One hundred eighty-six points representing 75 soil series in the Northern Mississippi Valley Loess Hills and 149 points representing 58 soil series in Palouse and Nez Perce Prairies were sampled from a statistically representative subset of NRI sample points and analyzed for 20 soil attributes. Factor analysis was used to identify soil quality factors and discriminant analysis was used to identify factors and indicators most sensitive to land use within each region. In the Northern Mississippi Valley Loess Hills, five soil quality factors were identified. Discriminant analysis selected potentially mineralizable N (PMN), microbial biomass C (MBC), water stable aggregates (WSA), and total organic C (TOC) as the most discriminating attributes between land uses. In the Palouse and Nez Perce Prairies, six factors were identified. Discriminant analysis selected TOC and total N as the most discriminating attributes between land uses. The soil quality factors were similar among three of the four regions, but TOC was the only indicator common to all regions for distinguishing among land uses.

Soil quality has been defined as "the capacity of a soil to function within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Parkin, 1994). Soil functions that soil quality influences include the ability (i) to accept, hold, and release nutrients and other chemical constituents; (ii) to accept, hold, and release water to plants and surface and groundwater recharge; (iii) to promote and sustain root growth; (iv) to maintain suitable soil biotic habitat; and (v) to respond to management and resist degradation (Larson and Pierce, 1991). Maintaining or improving soil quality can provide economic benefits in the form of increased productivity, more efficient use of nutrients and pesticides, improvements in water and air quality, and amelioration of greenhouse gas emissions (USDA-Economic Research Service, 1997).

Because of its importance, a quantitative assessment of soil quality is needed to determine the sustainability of land management systems as related to agricultural production practices, and to assist government agencies in formulating and evaluating sustainable agricultural and land use policies (Doran and Parkin, 1996). However, soil quality cannot be measured directly, but must be inferred from soil quality indicators. Soil quality indicators are measurable soil attributes that influence the capacity of soil to perform crop production or environmental functions and are sensitive to change in land use, management, or conservation practices. However, many soil attributes are highly correlated (Larson and Pierce, 1991; Seybold et al., 1997). Correlated soil attributes do not change independently to changes in management, but respond as a group, integrating many complex interactions among biological, chemical, and physical soil processes. Single attribute indicators do not reflect interacting changes in soil quality that may occur with changes in management because of correlation among soil attributes. A more accurate assessment of soil quality may be achieved by evaluating several soil attributes simultaneously using statistical procedures that account for correlation among soil attributes.

Multivariate statistical analyses, such as factor analysis, provide techniques for studying the relationships among correlated variables (James and McCulloch, 1990; Johnson and Wichern, 1992). A regional-scale study of soil quality (Brejda et al., 2000) used factor analysis to statistically group 20 soil attributes on the basis of their intercorrelations into five factors for the Ascalon (fine-loamy, mixed, superactive, mesic Aridic Argiustoll) soil in the Central High Plains and six soil quality factors for the Amarillo (fine-loamy, mixed, thermic Aridic Paleustalf) soil in the Southern High Plains. Because each of these factors contributed to one or more soil functions, they were considered to represent soil quality factors and should not be confused with factors of soil formation proposed by Jenny (1980). The soil quality factors in each region were analyzed by analysis of variance and discriminant analysis to determine which were sensitive to differences in land use and could serve as potential indicators of soil quality at a regional scale. However, this analysis was done using only a single soil series within each region. Therefore, conclusions from analysis of the Ascalon and Amarillo soils are limited to these or similar soil series. Broader conclusions may be made concerning the composition of soil quality factors and their variation with different

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Published in Soil Sci. Soc. Am. J. 64:2125–2135 (2000).

Abbreviations: CEC, cation-exchange capacity; CRP, Conservation Reserve Program; MBC, microbial biomass C; MEP, Mehlich III extractable P; MLRA, Major Land Resource Area; NRI, National Resource Inventory; PMC, potentially mineralizable C; PMN, potentially mineralizable N; TOC, total organic C; WSA, water stable aggregate.

*, ** Significant at the 0.05 and 0.01 levels of probability, respectively.

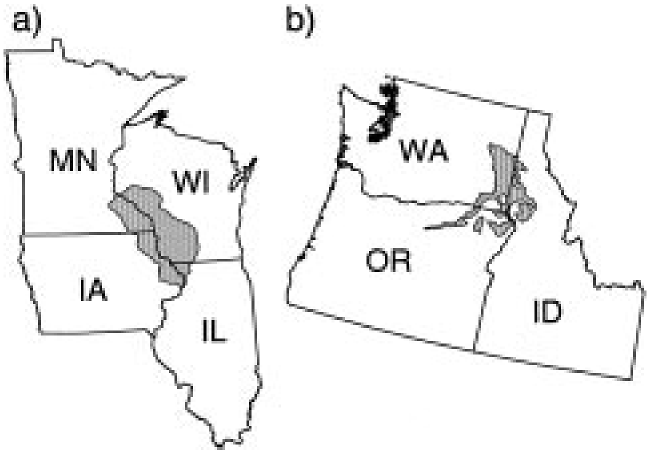

Fig. 1. Geographic distribution (shaded areas) of (a) the Northern Mississippi Valley Loess Hills, and (b) the Palouse and Nez Perce Prairies Major Land Resource Areas.

land uses or conservation practices if a large and diverse population of soil series from different regions were analyzed. However, the greater variation inherent in multiple soil series studies could mask our ability to identify soil quality factors or detect change in these factors with different land uses at the regional scale. Our objectives were (i) to identify soil quality factors at a regional scale for samples taken from a diverse population of soil series, (ii) to determine which factors vary significantly with land use, (iii) to select soil attributes within these factors that can be used as soil quality indicators with the NRI to assess effects of land use or soil conservation programs on soil quality, and (iv) compare these results with a similar study involving only a single soil series.

MATERIALS AND METHODS

Two Major Land Resource Areas (MLRA), designated the Northern Mississippi Valley Loess Hills and the Palouse and Nez Perce Prairies, were selected for this study. The Northern Mississippi Valley Loess Hills covers 27 090 km^2 and is located in southwestern Wisconsin, northeastern Iowa, and southeastern Minnesota (Fig. 1a). Elevation ranges from 200 m on river valley floors to 400 m on the highest ridges. Average annual precipitation ranges from 750 to 900 mm with two-thirds or more falling during the growing season. Average annual temperature ranges from 7 to 10°C. About 40% of the MLRA is cultivated for corn (*Zea mays* L.), soybean (*Glycine max* L.), and small grain production; 20% is in permanent pasture and hay land; and the remainder is forested (USDA-SCS, 1981).

The Palouse and Nez Perce Prairies covers 23 140 km^2 and is located in southeastern Washington, northwestern Idaho, and northeastern Oregon (Fig. 1b). Elevation ranges from 600 to 1200 m. Average annual precipitation ranges from 375 to 625 mm and is evenly distributed through the fall, winter, and spring, with the summers being relatively dry. Average annual temperature ranges from 7 to 12°C. About 50% of the MLRA is crop land, 40% is rangeland and permanent pasture, and the remainder is forested (USDA-SCS, 1981). Most of the crop land is nonirrigated to wheat (*Triticum aestivum* L.), spring pea (*Pisum sativum* L.), and lentil (*Lens culinaris* L.).

Experimental Design

A statistically representative sample of 200 points were selected within each MLRA using the NRI sampling framework. Detailed descriptions of sample point selection within the NRI framework are presented elsewhere (Goebel and Baker, 1982; Nusser and Goebel, 1997; Nusser et al., 1998; Brejda et al., 2000). Some points were inaccessible, or fell on homesteads, urban areas, road pavement, or rock outcrops. These points were not sampled. As a result, only 186 points were actually sampled in the Northern Mississippi Valley Loess Hills, and 149 points were sampled in the Palouse and Nez Perce Prairies. Points were selected at random, without regard to soil series or land use. This resulted in sampling 75 different series in the Northern Mississippi Valley Loess Hills, and 58 different series in the Palouse and Nez Perce Prairies. The 186 soils sampled in the Northern Mississippi Valley Loess Hills were predominately Alfisols (n = 127), but also included Mollisols (n = 32), Entisols (n = 22), Inceptisols (n = 2), and Histosols (n = 1). At two sampling points, the soil series were not classified. The 149 soils sampled in the Palouse and Nez Perce Prairies were predominately Mollisols (n = 136), with a few Alfisols (n = 7), Inceptisols (n = 2), Andisols (n = 2), and Entisols (n = 1). At one sampling point, the soil series was not classified.

Soil Sampling and Analysis

At each sample point a soil pit was dug, the depth of the A horizon was measured, and A horizon hue, value, and chroma were determined using a Munsell color chart. If the soil had been recently cultivated duplicate 1000-cm^3 soil samples were collected from the 0- to 10-cm depth. If the soil had not been cultivated, samples were taken from the 0- to 2.5- and 2.5- to 10-cm depth. For this analysis all data were analyzed for the 0- to 10-cm depth by taking a weighted average of samples taken at the 0- to 2.5- and 2.5- to 10-cm depths. One of the samples for each soil was used for biological analysis and was placed in a cooler with ice packs for transport to the lab. The other sample was used for physical and chemical analysis and was sent to the lab without refrigeration.

Samples collected for biological analysis were analyzed for MBC (Tate et al., 1988) using the correction factor (k = 0.33) of Sparling and West (1988), and potentially mineralizable C (PMC) and PMN on the <2-mm fraction using procedures outlined by Drinkwater et al. (1996) with the following modifications. Forty grams of soil were used in the analysis instead of 10 g, and samples were incubated for 35 d at 25°C instead of 30°C. Detailed descriptions of the methods used for biological analyses are given in the companion paper (Brejda et al., 2000).

Samples collected for physical and chemical analyses were analyzed for sand, silt, and clay content (pipette method), and WSA using screens with 4-, 2-, 1-, 0.5-, and 0.25-mm openings (Kemper and Rosenau, 1986). Aggregate weights were summed from each sieve and divided by the sample weight to calculate total WSA content. Samples were also analyzed for pH (1:1 soil/water), TOC, total N, cation-exchange capacity (CEC), exchangeable Ca, Mg, K, and Na, and acidity. Standard soil survey lab methods (USDA-NRCS, 1996) were used in these analyses. The samples were also analyzed for Mehlich III extractable P (MEP) (Mehlich, 1984) measured using inductively coupled plasma emission spectroscopy. All physical and chemical analyses were done on the <2-mm sieved fraction. Detailed descriptions of the methods used for chemical and physical analyses are given in Brejda et al. (2000).

Statistical Analysis

Factor Analysis

Factor analysis was used to group the 20 soil attributes into statistical factors based on their correlation structure using PROC FACTOR in SAS (SAS Institute, 1989). Factor analysis was performed on standardized variables using the correlation matrix (Tables 1 and 4) to eliminate the effect of different measurement units on factor loadings (James and McCulloch, 1990; Johnson and Wichern, 1992). Factor loadings are the simple correlations between the soil attributes and each factor (Sharma, 1996). The 20 soil attributes analyzed were A horizon value, chroma, and depth; percentage sand, silt, and clay; WSA content; TOC; MBC; PMC; total N; PMN; MEP; pH; CEC; exchangeable Ca, Mg, K, Na; and acidity.

Because factor analysis was performed on standardized values of the soil attributes, each variable had a variance of one with a total variance of 20 for the entire data set. Eigenvalues are the amount of variance explained by each factor (Sharma, 1996). Factors with eigenvalues greater than one were retained for interpretation, because factors with eigenvalues less than one explained less variance than individual soil attributes. The retained factors were subjected to a varimax rotation. A varimax rotation redistributes the variance of significant factors to maximize the relationship between interdependent soil variables (SAS Institute, 1989).

Communalities estimate the portion of variance in each soil attribute explained by the factors. A high communality for a soil attribute indicates a high proportion of its variance is explained by the factors. In contrast, a low communality for a soil attribute indicates much of that attribute's variance remains unexplained. Less importance should be ascribed to soil attributes with low communalities when interpreting variable associations represented by each factor.

The sample points used in this study are also sampled every 5 yr as part of the NRI. As a result, information on land use practices from 1989 through 1996 was available for each sample point. This information was used to place each point into one of four land use categories: (i) continuous crop land, (ii) Conservation Reserve Program (CRP) land, (iii) perennial forages comprised of native range or introduced grasses and legumes used for pasture and hay production, or (iv) forest and woodland. Factor scores from each observation were computed by SAS using the regression method (SAS Institute, 1989; Johnson and Wichern, 1992) and analyzed by analysis of variance using the GLM procedure with the four land use categories as the independent variable.

Discriminant Analysis

Discriminant analysis was used to select the statistical factor(s) that were most discriminating between the four land use categories. The analysis was done using PROC DISCRIM in SAS (SAS Institute, 1989). The covariance matrices for the land use groups were tested for equality at the $\alpha = 0.01$ significance level with the POOL = TEST option. The matrices were unequal in both regions, so the pooled within group covariance matrices and a quadratic discriminant function were used in the analysis (SAS Institute, 1989). Following selection of the most discriminating factor(s), the soil attributes that comprised these factors were also subjected to discriminant analysis to select soil quality indicators for each region. All soil attributes were tested for normality using the procedure of D'Agostino et al. (1990), and non-normally distributed soil attributes were $\log_e$ transformed prior to analysis (Brejda et al., 2000b).

RESULTS

Northern Mississippi Valley Loess Hills

Significant correlation ($P < 0.05$) was present between 137 of 190 soil attribute pairs for samples from the Northern Mississippi Valley Loess Hills (Table 1). A horizon value, chroma, depth, and percentage sand were negatively correlated with most other soil attributes, the highest being with TOC ($r = -0.36^{**}$ to -0.51^{**}). In contrast, percentage clay, WSA, TOC, MBC, total N, and PMN were positively correlated with most soil attributes other than those listed above. Cation-exchange capacity was strongly correlated with TOC content ($r = 0.82^{**}$). Exchangeable Ca and Mg were strongly correlated with each other and with CEC, TOC, and percentage clay. The large amount of correlation present among the 20 soil attributes indicates they can be grouped into homogenous sets of variables based on their correlation patterns (Sharma, 1996).

Each of the first five factors had eigenvalues greater than one (Table 2), and were retained for interpretation. These five factors explained >90% of the variance in percentage sand, TOC, total N, CEC, and exchangeable Ca, and 80% of the variance in percentage silt, MBC, PMC, PMN, MEP, pH, and exchangeable Mg, K, and acidity, as indicated by their communalities (Table 2). However, the first five factors explained <50% of the variance in A horizon depth, WSA content, and exchangeable Na. Less importance should be ascribed to A horizon depth, WSA content, and exchangeable Na when interpreting the factors.

The first factor had high positive loadings (>0.80) on TOC, MBC, PMC, total N, and PMN, and a moderate (0.50–0.60) positive loading on CEC, exchangeable Ca, and WSA content (Table 2). A horizon depth had a weak negative loading (−0.42) on the first factor, but the low communality for this attribute indicates it is not important for interpreting the factor. The first factor was termed the *organic matter factor* because most of the soil attributes comprising this factor are important components of soil organic matter quality (Gregorich et al., 1994). Grouping of WSA with the organic matter factor resulted from the consistent correlation between WSA and TOC ($r = 0.37^{**}$), MBC ($r = 0.38^{**}$), and PMN ($r = 0.38^{**}$). The main binding agents of soil aggregates are organic materials, including the decomposition products of plants, animals, and microorganisms, as well as products of microbial synthesis (Lynch and Bragg, 1985).

The second factor had high positive loadings for percentage silt (0.88) and clay (0.76), and a high negative loading for percentage sand (−0.95) (Table 2), and was termed the *soil texture factor*. Grouping CEC with the organic matter factor rather than with soil textural properties resulted from the stronger correlation between CEC and TOC ($r = 0.82^{**}$) than between CEC and percentage clay ($r = 0.64^{**}$) (Table 1).

The third factor had positive loadings for pH (0.89) and exchangeable Mg (0.71), a negative loading for exchangeable acidity (−0.72) (Table 2), and was termed the *soil acidity factor*. Grouping these three soil attributes together resulted from strong correlations between soil pH and exchangeable Mg ($r = 0.68^{**}$), and acidity ($r = -0.63^{**}$) (Table 1).

The fourth factor had moderate positive loadings for A horizon value and chroma, and was termed the *soil color factor*. The fifth factor had high positive loadings

Table 1. Correlations among physical, chemical, and biological soil attributes in the 0- to 10-cm depth in the Northern Mississippi Valley Loess Hills Major Land Resource Area (n = 186).

	A horizon														Exchangeable				
Soil attribute	Value	Chroma	Depth	Sand	Silt	Clay	WAS†	TOC‡	MBC§	PMC¶	Total N	PMN#	Mehlich P	pH	CEC††	Ca	Mg	K	Na
A horizon chroma	0.33**																		
A horizon depth	0.30**	0.35**																	
Sand	−0.30*	−0.16*	−0.33**																
Silt	0.33**	0.18*	0.29**	−0.96**															
Clay	0.11	0.04	0.29**	−0.71**	0.49**														
WSA†	−0.18*	−0.18*	−0.29**	0.24**	−0.23**	−0.16*													
TOC‡	−0.51**	−0.36**	−0.37**	0.07	−0.15*	0.18*	0.37**												
MBC§	−0.39**	−0.22**	−0.35**	−0.04	−0.04	0.23**	0.38**	0.86**											
PMC¶	−0.28**	−0.16	−0.31**	−0.06	−0.01	0.22**	0.27**	0.76**	0.83**										
Total N	−0.49**	−0.35**	−0.32**	−0.08	−0.01	0.29**	0.34**	0.96**	0.88**	0.76**									
PMN#	−0.34**	−0.21**	−0.36**	0.01	−0.03	0.04	0.38**	0.72**	0.80**	0.81**	0.74**								
Mehlich P	−0.18*	−0.10	0.11	0.03	−0.07	0.10	−0.04	0.13	0.11	0.26**	0.13	0.12							
pH	−0.01	0.00	0.22*	−0.33**	0.24**	0.45**	−0.08	0.24**	0.24**	0.21**	0.25**	−0.02	0.26**						
CEC††	−0.37**	−0.28**	−0.12	−0.32**	0.16*	0.64**	0.19**	0.82**	0.76**	0.63**	0.87**	0.54**	0.12	0.41**					
Exchangeable Ca	−0.34**	−0.25**	−0.10	−0.29**	0.15*	0.53*	0.17*	0.79**	0.72**	0.58**	0.81**	0.47**	0.14	0.59**	0.90**				
Exchangeable Mg	−0.09	−0.09	0.05	−0.38**	0.19**	0.73**	0.05	0.53**	0.53**	0.43**	0.56**	0.24**	0.18*	0.68**	0.77**	0.74**			
Exchangeable K	−0.18*	−0.11	0.06	−0.16*	0.09	0.30**	0.06	0.32**	0.33**	0.47**	0.33**	0.31**	0.78**	0.33**	0.33**	0.28**	0.38**		
Exchangeable Na	0.05	−0.05	−0.09	−0.07	0.02	0.18*	0.07	0.15*	0.22**	0.17*	0.20**	0.15*	0.05	0.00	0.19*	0.23**	0.09	0.07	
Exchange. Acidity	−0.31**	−0.31**	−0.32**	0.15*	−0.15*	−0.10*	0.23**	0.34**	0.22**	0.25**	0.37**	0.44**	−0.13	−0.63**	0.23**	−0.04	−0.23**	−0.08	0.08

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† WSA = water stable aggregates.
‡ TOC = total organic C.
§ MBC = microbial biomass C.
¶ PMC = potentially mineralizable C.
# PMN = potentially mineralizable N.
†† CEC = cation-exchange capacity.

Table 2. Rotated factor loadings and communalities of a five-factor model of physical, chemical, and biological soil attributes in the Northern Mississippi Valley Loess Hills Major Land Resource Area.

	Factor					
Soil attributes	1	2	3	4	5	Communalities
A horizon value	−0.26	0.27	−0.02	0.68	−0.15	0.63
A horizon chroma	−0.12	0.08	0.07	0.74	−0.03	0.57
A horizon depth	−0.42	0.37	0.22	0.25	0.18	0.46
Sand	−0.03	−0.95	−0.12	−0.15	−0.01	0.94
Silt	−0.03	0.88	0.01	0.21	−0.01	0.82
Clay	0.17	0.76	0.41	−0.08	0.07	0.78
WSA†	0.52	−0.35	−0.06	0.04	−0.10	0.41
Total organic C	0.83	−0.05	0.22	−0.42	0.06	0.92
Microbial biomass C	0.90	0.01	0.19	−0.17	0.08	0.89
Potentially mineral. C	0.85	0.04	0.06	−0.07	0.30	0.82
Total N	0.84	0.10	0.18	−0.42	0.07	0.93
Potentially mineral. N	0.87	−0.01	−0.18	−0.11	0.16	0.82
Mehlich P	0.02	−0.05	0.12	−0.08	0.93	0.89
pH	0.08	0.18	0.89	0.02	0.19	0.86
CEC‡	0.68	0.38	0.38	−0.43	0.03	0.94
Exchangeable Ca	0.63	0.26	0.57	−0.32	0.01	0.90
Exchangeable Mg	0.40	0.35	0.71	−0.17	0.10	0.84
Exchangeable K	0.26	0.13	0.14	−0.05	0.88	0.89
Exchangeable Na	0.37	0.10	−0.05	0.25	0.00	0.21
Exchangeable acidity	0.37	0.05	−0.72	−0.43	−0.10	0.86
Eigenvalues	5.64	3.01	2.72	2.13	1.91	

† WSA = water stable aggregates.
‡ CEC = cation-exchange capacity.

for exchangeable K and MEP (Table 2), and was termed the *fertility management factor*.

Factor scores for all five factors varied significantly with land use (Table 3). Average scores for the organic matter factor were negative for crop land and positive for land in perennial forages and forest and woodlands (Table 3). Organic matter factor scores were also negative for land in CRP, but the magnitude of the scores were not as large as for crop land. This pattern is consistent with the effects of management on soil organic matter quality (Gregorich et al., 1994).

Soil texture factor scores varied significantly between soils under forest and woodland vs. the other three land uses (Table 3). Soils under forest and woodland had

Table 3. Soil attribute means and factor scores with different land uses in the Northern Mississippi Valley Loess Hills Major Land Resource Area.

Soil attribute	Cropland	CRP	Perennial forages	Forest & Woodland	SE	ANOVA $P > F$
Number of points sampled	69	23	42	52		
A horizon value	3.19	3.26	3.14	2.52	0.10	0.01
A horizon chroma	2.00	2.09	1.86	1.37	0.09	0.01
A horizon depth, cm	19.1	20.0	15.5	9.1	0.8	0.01
Sand, %	14.7	9.3	12.3	29.9	3.0	0.01
Silt, %	66.1	71.5	69.5	56.3	2.5	0.01
Clay, %	19.3	19.1	18.2	13.9	0.9	0.01
WSA†, g kg^{-1}	410	590	620	640	21	0.01
TOC‡, g kg^{-1}	19.2	20.9	30.6	39.4	2.35	0.01
MBC§, mg kg^{-1}	370	450	750	840	55	0.01
PMC¶, mg CO_2 kg^{-1} d^{-1}	67	80	102	104	7.4	0.01
Total N, g kg^{-1}	1.96	2.1	2.91	3.25	0.17	0.01
PMN#, mg N kg^{-1}	43.2	48.7	84.8	91.7	5.2	0.01
Mehlich P, mg kg^{-1}	72	36	53	37	8	0.01
pH (1:1 soil/H_2O)	6.46	6.22	6.33	5.95	0.11	0.01
CEC††, cmol kg^{-1}	16.2	16.4	19.0	20.2	1.1	0.05
Exchangeable Ca, cmol kg^{-1}	10.9	10.3	13.8	14.0	1.0	0.05
Exchangeable Mg, cmol kg^{-1}	4.4	3.9	4.6	3.8	0.4	NS
Exchangeable K, cmol kg^{-1}	0.58	0.48	0.54	0.41	0.06	NS
Exchangeable Na, cmol kg^{-1}	0.06	0.05	0.12	0.07	0.02	NS
Exchangeable acidity, cmol kg^{-1}	5.4	6.2	6.7	8.7	0.4	0.01
			Factor scores			
Factor 1 (organic matter)	−0.65	−0.23	0.49	0.57	0.12	0.01
Factor 2 (texture)	0.22	0.33	0.13	−0.54	0.14	0.01
Factor 3 (acidity)	0.27	−0.03	−0.02	−0.33	0.14	0.05
Factor 4 (color)	0.08	0.42	0.41	−0.61	0.13	0.01
Factor 5 (fertility management)	0.36	−0.15	−0.02	−0.39	0.14	0.01

† WSA = water stable aggregates.
‡ TOC = total organic C.
§ MBC = microbial biomass C.
¶ PMC = potentially mineralizable C.
# PMN = potentially mineralizable N.
†† CEC = cation-exchange capacity.

higher sand content, and lower silt and clay content, than soils under crop land, CRP, or perennial forages (Table 3). This suggests that soil texture may have influenced land use in this MLRA, in which landowners left sandier soils in forest rather than cultivate them for crop production.

Soil acidity factor scores were positive under crop land, near zero with land in CRP and perennial forages, and negative under forest and woodland (Table 3). Positive acidity factor scores for crop land resulted from higher soil pH and exchangeable Mg levels, and lower exchangeable acidity levels, probably resulting from lime applications as part of crop production practices with this land use.

Soil color factor scores were negative under forest and woodland and positive under the other three land uses. Forest and woodland had the lowest A horizon value and chroma, indicating darker soil colors, resulting in the lowest color factor scores. The highest soil color factor scores were under land in CRP and perennial forages, indicating lighter soil color. Crop land had intermediate soil color factor scores.

Fertility management factor scores were highest under crop land and land in perennial forages, probably resulting from the application of K and P as part of crop production practices (Table 3). Forest and woodland had the lowest fertility management factor scores, probably because this land use rarely receives K and P applications.

Discriminant analysis of the five factors indicated that the soil organic matter factor was the most powerful in discriminating between the four land use categories, based on the magnitude of their discriminant coefficients (Eq. [1]).

$$Y_1 = -0.86(\text{organic matter factor}) + 0.60(\text{texture factor}) + 0.54(\text{fertility factor}) + 0.53(\text{color factor}) + 0.46(\text{acidity factor}) \quad [1]$$

However, no single factor dominated the discriminant function in this MLRA. This is in contrast to results from the Central High Plains in which the discriminant coefficient for the soil organic matter factor was fourfold larger than the coefficients for soil texture, acidity, and color factors, and more than tenfold larger than the coefficient for the soil P factor (Brejda et al., 2000a).

Discriminant analysis of soil attributes that comprise the soil organic matter factor indicated that PMC, MBC, WSA, and TOC were the most powerful soil attributes in discriminating between the different land uses (Eq. [2]).

$$Y_2 = 0.65(\text{PMN}) + 0.61(\text{MBC}) + 0.58(\text{WSA}) + 0.55(\text{TOC}) + 0.45(\text{total N}) + 0.36(\text{PMC}) + 0.16(\text{CEC}) + 0.08(\text{Exch. Ca}) \quad [2]$$

No one or two soil attributes clearly stood out as dominant indicators for detecting changes in land use in this MLRA. This is in contrast to results from the Central and Southern High Plains where two soil attributes were identified for each region as potential indicators because of their sensitivity to change with land use (Brejda et al., 2000a).

Palouse and Nez Perce Prairies

Significant correlation was present between 114 of 190 soil attribute pairs in the Palouse and Nez Perce Prairies (Table 4). As with the Northern Mississippi Valley Loess Hills, A horizon value and chroma were negatively correlated with most soil attributes, whereas WSA, TOC, MBC, total N, and PMN were positively correlated with most soil attributes other than A horizon value and chroma. Cation-exchange capacity was strongly correlated with both TOC ($r = 0.77^{**}$) and percentage clay ($r = 0.67^{**}$).

The first six factors had eigenvalues greater than one (Table 5) and were retained for interpretation. The six factors explained >90% of the variance in percentage sand and silt, TOC, and CEC, and 80% of the variance in A horizon depth, percentage clay, total N, pH, exchangeable Ca, Mg, and acidity (Table 5). However, the six factors explained <60% of the variance in PMC, PMN, and MEP, and <50% of the variance in MBC.

The first factor had large positive loadings (≥0.80) for TOC and total N, and moderate positive loadings (0.67–0.73) for MBC, PMC, PMN, and MEP (Table 5). This factor was termed the *organic matter factor* because most of the soil attributes that comprise it are components of soil organic matter quality (Gregorich et al., 1994). The soil organic matter factor was very similar between the Palouse and Nez Perce Prairies and the Northern Mississippi Valley Loess Hills in terms of the soil attributes that comprised them (Tables 2 and 5).

The second factor had positive loadings (0.65–0.80) for percentage clay, CEC, and exchangeable Ca and Mg (Table 5) and was termed the *exchangeable bases factor*. Exchangeable Ca and Mg were significantly correlated with CEC ($r = 0.80^{**}$ and $r = 0.64^{**}$) and percentage clay ($r = 0.40^{**}$ and $r = 0.42^{**}$).

The third factor had positive loadings for percentage sand (0.88) and WSA (0.66), a high negative factor loading (−0.95) for percentage silt, and a weak negative (−0.39) factor loading for percentage clay (Table 5). This grouping resulted from the significant negative correlation between WSA and percentage silt ($r = -0.54^{**}$), and positive correlation between WSA and percentage sand ($r = 0.40^{**}$) (Table 4). This factor represented the *soil texture factor* for the Palouse and Nez Perce Prairies. It was similar to the soil texture factor for the Northern Mississippi Valley Loess Hills, except that in the Palouse and Nez Perce Prairies it contained WSA and the loading on percentage clay was low (Tables 2 and 5).

The fourth factor had moderate positive loadings (0.57–0.73) for pH, and exchangeable K and Na, a moderate negative loading for exchangeable acidity (−0.58), and represented the soil acidity factor in the Palouse and Nez Perce Prairies (Table 5). The soil acidity factor was similar between the two MLRA (Tables 2 and 5), except that for the Palouse and Nez Perce Prairies, which contained the monovalent bases (K and Na), rather than the divalent bases (Ca and Mg).

Table 4. Correlations among physical, chemical, and biological soil attributes in the 0- to 10-cm depth in the Palouse and Nez Perce Prairies Major Land Resource Area (n = 149).

	A horizon														Exchangeable				
Soil attribute	Value	Chroma	Depth	Sand	Silt	Clay	WSA†	TOC‡	MBC§	PMC¶	Total N	PMN#	Mehlich P	pH	CEC††	Ca	Mg	K	Na
A horizon chroma	0.46**																		
A horizon depth	−0.19*	−0.06																	
Sand	−0.29**	0.24**	−0.14																
Silt	−0.19*	−0.10	0.15	−0.88**															
Clay	−0.31**	−0.35**	0.06	−0.73**	−0.32**														
WSA†	0.09	0.11	−0.04	0.40**	−0.54**	−0.03													
TOC‡	−0.23**	−0.21*	0.07	−0.15	−0.05	0.24**	0.42**												
MBC§	−0.08	−0.14	0.05	0.02	−0.02	0.00	0.29**	0.58**											
PMC¶	−0.06	0.04	0.11	0.06	−0.01	−0.10	0.28**	0.47**	0.46**										
Total N	−0.27**	−0.22**	−0.17*	−0.18*	0.06	0.28**	0.33**	0.94**	0.53**	0.45**									
PMN#	−0.13	−0.07	0.12	−0.05	0.01	0.09	0.43**	0.64**	0.39**	0.50**	0.65**								
Mehlich P	−0.07	0.01	0.04	−0.03	0.09	−0.07	0.32**	0.43**	0.27**	0.31**	0.31**	0.31**							
pH	0.13	0.05	0.06	0.40**	−0.38**	−0.26**	0.33**	0.09	0.14	0.25*	0.10	0.21**	0.03						
CEC††	−0.33**	−0.37**	0.11	−0.42**	0.13	0.67**	0.25**	0.77**	0.37**	0.27**	0.78**	0.43**	0.17*	0.07					
Exchangeable Ca	−0.23**	−0.32**	0.11	−0.20*	0.00	0.40**	0.23**	0.61**	0.30**	0.29**	0.63**	0.37**	0.16	0.46**	0.80**				
Exchangeable Mg	−0.15	−0.19*	0.10	−0.05	−0.22**	0.42**	0.39**	0.34**	0.22**	0.28**	0.36**	0.20*	−0.05	0.40**	0.64**	0.62**			
Exchangeable K	−0.27**	−0.22**	0.17*	−0.11	−0.03	−0.18*	0.19*	0.42**	0.21**	0.37**	0.46**	0.37**	0.46**	0.35**	0.30**	0.48**	0.18*		
Exchangeable Na	−0.19*	−0.28**	0.01	−0.08	0.06	0.07	−0.11	0.10	0.06	−0.01	0.14	0.03	−0.02	0.30**	0.13	0.42**	0.19*	0.32**	
Exchange. acidity	−0.27**	−0.28**	0.00	−0.50**	−0.34**	0.50**	−0.07	0.50**	0.27**	0.02	0.42**	0.12	0.21*	−0.58**	0.47**	0.06	−0.08	−0.13	−0.03

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† WSA = water stable aggregates.
‡ TOC = total organic C.
§ MBC = microbial biomass C.
¶ PMC = potentially mineralizable C.
# PMN = potentially mineralizable N.
†† CEC = cation-exchange capacity.

Table 5. Rotated factor loadings and communalities for a six-factor model of physical, chemical, and biological soil attributes in the Palouse and Nez Perce Prairies Major Land Resource Area.

	Factor						
Soil attributes	1	2	3	4	5	6	Communalities
A horizon value	−0.10	−0.11	0.12	0.01	0.76	−0.27	0.69
A horizon chroma	−0.02	−0.21	0.06	−0.10	0.80	0.07	0.69
A horizon depth	0.08	0.05	−0.11	0.01	−0.13	0.87	0.80
Sand	−0.03	−0.35	0.88	0.17	0.13	−0.05	0.96
Silt	0.06	−0.03	−0.95	−0.05	−0.01	0.10	0.92
Clay	−0.04	0.76	−0.39	−0.26	−0.25	−0.04	0.87
WSA†	0.45	0.26	0.66	−0.08	0.13	0.00	0.73
Total organic C	0.86	0.35	−0.01	−0.04	−0.19	−0.08	0.90
Microbial biomass C	0.67	0.11	0.09	−0.02	−0.06	−0.10	0.48
Potentially mineral. C	0.67	0.05	0.04	0.16	0.19	0.22	0.57
Total N	0.80	0.40	−0.04	0.02	−0.21	0.04	0.84
Potentially mineral. N	0.73	0.18	0.06	0.04	0.04	0.17	0.59
Mehlich P	0.67	−0.26	−0.06	0.03	−0.05	−0.04	0.53
pH	0.11	0.19	0.39	0.73	0.23	0.13	0.81
CEC‡	0.50	0.77	−0.14	0.00	−0.27	−0.02	0.94
Exchangeable Ca	0.40	0.65	−0.05	0.50	−0.18	−0.02	0.87
Exchangeable Mg	0.12	0.80	0.24	0.25	−0.02	0.13	0.80
Exchangeable K	0.54	−0.13	0.06	0.57	−0.31	0.18	0.76
Exchangeable Na	−0.01	0.11	−0.17	0.70	−0.33	−0.24	0.70
Exchangeable acidity	0.35	0.17	−0.37	−0.58	−0.38	−0.26	0.84
Eigenvalues	4.32	2.99	2.73	2.14	1.98	1.14	

† WSA = water stable aggregates.
‡ CEC = cation-exchange capacity.

The fifth factor had high positive loadings for A horizon value and chroma, and was identical to the soil color factor observed for the Northern Mississippi Valley Loess Hills (Tables 2 and 5).

The sixth factor had a high positive factor loading (0.87) only on A horizon depth (Table 5), and was termed the *A horizon depth factor*. A horizon depth was not an important soil attribute in the Northern Mississippi Valley Loess Hills.

Factor scores for five of the six factors varied significantly with land use (Table 6). Only the soil acidity factor did not vary significantly with land use. Organic matter factor scores were lowest under CRP followed by continuous crop land, and highest under land in perennial forages and forest and woodland. This pattern is similar to the pattern for organic matter factor scores in the Northern Mississippi Valley Loess Hills, and probably reflects the effects of management on soil organic matter.

Exchangeable bases factor scores were positive in land under perennial forages, as a result of the highest exchangeable Ca and Mg concentrations under this land use (Table 6). The other three land uses had negative exchangeable bases factor scores with land in CRP having the lowest scores (Table 6).

Soil texture factor scores were negative for crop land because of a higher silt content and lower sand and WSA content compared with the other land uses (Table 6). Soil texture factor scores were highest for land in perennial forages and forest and woodland, primarily because WSA concentrations were highest in soil under these land uses (Table 6).

Soil color factor scores were negative for crop land and positive for land in CRP, perennial forages, and woodland (Table 6). Crop land had the lowest A horizon value and chroma (Table 6), indicating darker soil colors. This is opposite to the pattern observed in the Northern Mississippi Valley Loess Hills, where crop land tended to have higher A horizon value and chroma, indicating lighter soil colors (Table 3).

A horizon depth factor scores followed the same pattern as the soil attribute associated with it. A horizon depth was deepest with land in perennial forages, resulting in large, positive depth factor scores, and shallowest in forest and woodland, resulting in large, negative depth factor scores (Table 6). A horizon depth, and depth factor scores were intermediate for crop land and land in CRP.

Discriminant analysis of the six factors indicated the soil organic matter factor, followed by the texture and color factors were the most powerful in discriminating between the four land use categories, based upon the magnitude of their discriminant coefficients (Eq. [3]).

$$Y_3 = 0.81(\text{organic matter factor}) + 0.71(\text{texture factor}) + 0.67(\text{color factor}) + 0.39(\text{exchangeable bases factor}) + 0.23(\text{A horizon depth factor}) + 0.12(\text{acidity}) \quad [3]$$

However, as with the Northern Mississippi Valley Loess Hills, no single factor dominated the discriminant function with the data for the Palouse and Nez Perce Prairies.

Discriminant analysis of soil attributes that comprise the soil organic matter factor indicated that total N and TOC were the most powerful soil attributes in discriminating between land uses (Eq. [4]).

$$Y_4 = -2.26(\text{Total N}) + 2.23(\text{TOC}) + 0.48(\text{MBC}) + 0.26(\text{PMC}) + 0.20(\text{PMN}) + 0.11(\text{MEP}) \quad [4]$$

The discriminant coefficients for total N and TOC were more than fourfold larger than the coefficient for MBC, and 20-fold larger than the coefficient for MEP (Eq. [4]). Both TOC and total N varied significantly with

Table 6. Soil attribute means and factor scores with different land uses in the Palouse and Nez Perce Prairies Major Land Resource Area.

Soil attribute	Cropland	CRP	Perennial forages	Forest & woodland	SE	ANOVA $P > F$
Number of points sampled	77	12	42	18		
A horizon value	2.29	2.67	2.52	2.61	0.10	0.05
A horizon chroma	1.74	1.83	2.02	1.94	0.08	0.05
A horizon depth, cm	20.2	19.0	22.0	17.0	1.4	NS
Sand, %	12.9	19.8	20.5	24.0	2.1	0.01
Silt, %	66.7	62.7	60.7	61.7	1.5	0.01
Clay, %	20.4	17.5	18.8	14.3	1.0	0.01
WSA†, g kg^{-1}	200	260	400	430	23	0.01
TOC‡, g kg^{-1}	21.5	16.2	29.1	36.7	1.75	0.01
MBC§, mg kg^{-1}	280	330	440	700	50	0.01
PMC¶, mg kg^{-1} d^{-1}	460	480	770	750	50	0.01
Total N, g kg^{-1}	1.83	1.34	2.46	2.41	0.13	0.01
PMN#, mg N kg^{-1}	14.0	12.6	27.8	27.1	2.3	0.01
Mehlich P, mg kg^{-1}	42	27	44	84	7	0.01
pH (1:1 soil/H_2O)	5.73	6.12	6.44	6.19	0.10	0.01
CEC††, cmol kg^{-1}	21.5	16.9	23.9	24.2	1.0	0.01
Exchangeable Ca, cmol kg^{-1}	13.6	9.8	15.5	15.3	0.9	0.01
Exchangeable Mg, cmol kg^{-1}	2.9	2.4	4.4	3.5	0.2	0.01
Exchangeable K, cmol kg^{-1}	1.19	0.90	1.38	1.57	0.12	NS
Exchangeable Na, cmol kg^{-1}	0.16	0.14	0.11	0.08	0.02	NS
Exchangeable acidity, cmol kg^{-1}	9.1	7.0	6.9	10.0	0.6	0.01
			Factor scores			
Factor 1 (organic matter)	−0.36	−0.63	0.36	1.11	0.14	0.01
Factor 2 (exchangeable bases)	−0.13	−0.46	0.48	−0.26	0.16	0.01
Factor 3 (texture)	−0.37	0.11	0.44	0.48	0.15	0.01
Factor 4 (acidity)	−0.06	0.01	0.17	−0.15	0.16	NS
Factor 5 (color)	−0.35	0.15	0.51	0.23	0.15	0.01
Factor 6 (A horizon depth)	−0.09	−0.12	0.39	−0.43	0.16	0.05

† WSA = water stable aggregates.
‡ TOC = total organic C.
§ MBC = microbial biomass C.
¶ PMC = potentially mineralizable C.
# PMN = potentially mineralizable N.
†† CEC = cation-exchange capacity.

land use with values decreasing in the order: forest and woodland > perennial forages > crop land > CRP (Table 6). Because TOC and total N were highly correlated ($r = 0.96^{**}$), they may be redundant as indicators. Because of this redundancy, TOC may be the better soil quality indicator because it influences a wide range of soil functions including infiltration, aeration, water retention, aggregate formation, bulk density, pH, buffer capacity, cation-exchange properties, mineralization, and the activity of soil organisms (Larson and Pierce, 1991; Seybold et al., 1997).

DISCUSSION

Based on the soil attributes that comprised them, all of the factors identified using factor analysis contribute to one or more soil functions proposed by Larson and Pierce (1991), and therefore are considered to be soil quality factors. The soil organic matter and texture factors contribute to the ability of the soil to accept, hold, and release nutrients and other chemical constituents, accept, hold, and release water to plants and for surface and groundwater recharge, promote and sustain root growth, maintain suitable soil biotic habitat, and respond to management and resist degradation (Larson and Pierce, 1991). The soil acidity and exchangeable bases factors contributes to the ability of the soil to supply nutrients and promote and sustain root growth. The fertility management factor is important in supplying K and P to the plant and promoting root growth. The A horizon depth factor influences seedling growth and the ability of the soil to resist degradation, and the color factor influences soil temperature and thus mineralization rates.

The reader should be aware that the soil quality factors identified in this manuscript and in the previous study (Brejda et al., 2000a) are not unique. Different results may have occurred if a different set of soil attributes had been analyzed, or had we used the covariance matrix or a different rotation in factor analysis. Some potentially important soil quality indicators were not included in these studies. The soil attributes we evaluated were selected by the USDA-NRCS as the soil properties they would consider monitoring in an assessment of soil quality using the NRI. The reason NRCS did not include other potential indicators, such as infiltration, is that the time and labor costs required to measure many other potential indicators were too high, making it infeasible to do on a large number of samples or regional scale. Despite this limitation, the set of 20 soil attributes used in these studies includes most of the indicators recommended in minimum data sets proposed by Arshad and Coen (1992), Doran and Parkin (1994), Kennedy and Papendick (1995), and Larson and Pierce (1991, 1994).

With factor analysis using the covariance matrix, soil attributes with large variances can unduly influence the determination of factor loadings (Johnson and Wichern, 1992). We had no a priori reason to believe that soil attributes with large variances are potentially more important soil quality indicators. Rather, we agree with Schipper and Sparling (2000) that soil attributes with large variability may be poor soil quality indicators because they may be too imprecise for detecting changes in soil quality following changes in land use or soil conservation practices. By using the correlation matrix in factor analysis, in which each variable is standardized to have a variance of one, the unequal variance problem was eliminated.

The purpose of factor rotation is to achieve a simpler factor pattern that can be meaningfully interpreted (Sharma, 1996). There are many potential rotations that can be used, but no rules to follow in selection of a specific rotation. Rather, Sharma (1996) states, "the solution that gives a theoretically more plausible or acceptable interpretation of the resulting factors would be considered to be the 'correct' solution." We used the varimax rotation because it results in a factor pattern in which each variable loads highly on only one factor, and because it provided a "theoretically plausible and acceptable interpretation of the resulting factors."

The validity of our results from factor analysis is supported by the consistency in the factor patterns observed in three of the four MLRAs studied (Table 7). The five soil quality factors identified in the Northern Mississippi Valley Loess Hills, where 75 different soil series were sampled, were identical to the five soil quality factors identified in the Central High Plains where only the Ascalon soil series was sampled (Table 7) (Brejda et al., 2000). The soil attributes that comprised these factors were also similar (Table 7). For the Palouse and Nez Perce Prairies, where 58 different soil series were sampled, six soil quality factors were identified, four of which were similar to the soil quality factors identified in the Central High Plains and Northern Mississippi Valley Loess Hills (Table 7). This suggests that these soil quality factors are common to a wide range of soils and geographic regions.

In contrast, in the Southern High Plains where only the Amarillo soil series was sampled, four of the six soil quality factors identified were different from factors identified in the other three regions. Further study is needed to determine how and why the Amarillo soil differs in soil qualities.

Despite differences in parent material, climate, and sampling design, the two soil quality indicators selected for the Palouse and Nez Perce Prairies (TOC and total N) were identical to indicators selected for the Central

Table 7. Soil quality factors, with interpretive names in italics, and the soil attributes that comprise these factors in four different Major Land Resource Areas of the USA.

Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
		Central High Plains			
Organic matter	*Texture*	*Acidity*	*Color*	*Soil*	
TOC†	Sand	pH	Value	Mehlich extract. P	
MBC#	Silt	Exch. acidity	Chroma		
PMC‡	Clay	Exch. Ca			
Total N	CEC	Exch. Na			
PMN§	Exch. Mg				
WSA¶	Exch. K				
A horizon depth					
		Northern Mississippi Valley Loess Hills			
Organic matter	*Texture*	*Acidity*	*Color*	*Fertility*	
TOC†	Sand	pH	Value	Mehlich extract. P	
MBC#	Silt	Exch. acidity	Chroma	Exch. K	
PMC‡	Clay	Exch. Mg			
Total N					
PMN§					
WSA¶					
A horizon depth					
CEC††					
Exch. Ca					
		Palouse and Nez Perce Prairies			
Organic matter	*Texture*	*Acidity*	*Color*	*Exch. bases*	*A horizon depth*
TOC†	Sand	pH	Value	Clay	A horizon depth
MBC#	Silt	Exch. acidity	Chroma	CEC	
PMC‡	WSA¶	Exch. K		Exch. Ca	
Total N		Exch. Na		Exch. Mg	
PMN§					
Mehlich extract. P					
		Southern High Plains			
Soil C	*Texture*	*Acidity*	*Salinity*	*Aggregates*	*PMN§*
TOC†	Sand	pH	Exch. Mg	WSA¶	PMN§
PMC‡	Silt	Exch. acidity	Exch. Na	Value	
	Clay	Chroma			
	CEC	MBC#			
	Exch. Ca	Mehlich P			
	Exch. K				
	Total N				

† TOC = total organic C. MBC = microbial biomass C.
‡ PMC = potentially mineralizable C.
§ PMN = potentially mineralizable N.
¶ WSA = water stable aggregates.
†† CEC = cation-exchange capacity.

High Plains. Similarly, the two soil quality indicators selected for the Southern High Plains (TOC and WSA) were part of the set selected for the Northern Mississippi Valley Loess Hills (PMN, MBC, WSA, and TOC). Only TOC was selected as a soil quality indicator in all four regions. This result supports our previous conclusions (Brejda et al., 2000a). There may be no universal optimum set of indicators for monitoring soil quality on a regional scale in all regions of the USA. However, if only one soil attribute were used to monitor soil quality with the NRI, TOC appears to offer the greatest potential of all of the attributes we evaluated.

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